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Fiber Lasers X: Technology, Systems and Aplications

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<u>High Order Ribbon Fiber Modes, Simulations, and Experiments for High Power Amplifiers</u>

High average power fiber lasers from 10s of kW to greater than 100 kW are of interest to manufacturers and the defense industry. Theoretical limits on diffraction limited circular geometry fiber lasers limit the average power to 2 kW for narrowband and 10-36 kW for Broadband lasers (1). We have proposed an alternative ribbon fiber geometry to allow scaling of fiber lasers far above these limits in which a single high order ribbon mode with a high effective area is amplified and converted back to the fundamental mode once in free space (2,3). A 10 kW single frequency ribbon fiber amplifier design is presented and Beam Propagation Method (BPM) simulation results verify the approach.

The SBS limited ribbon fiber amplifier design is based on solving a quasi-three level rate equation system considering the effective area of the desired ribbon fiber mode, then checking the resulting amplifier against the SBS limited output power. Either decreases in amplifier length or increases in the ribbon fiber core cross-sectional area will increase the SBS limit threshold while decreasing the amplifier efficiency. An ideal design for a desired output power level, in this case 10 kW, will find the length and cross-sectional area combination in which the SBS threshold is just above the output power of the laser while maintaining high efficiency, > 80%. After finalizing a design based on solving the quasi-three level rate equation system, the design is tested in a BPM code which includes gain, modal noise, and Kerr non-linearities. The resulting 10 kW ribbon fiber design has a core cross-section of 500 µm x 38 µm and is 1.7 m long. The index cross-section of this fiber is shown in the figure below, along with intensity profile of the 19-lobed mode with 90 % single mode purity that was used for simulations.

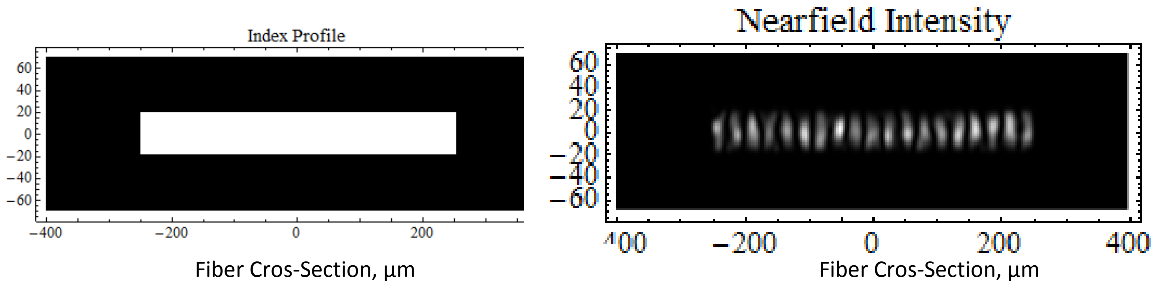

Figure 1: ribbon fiber rectangular core (a) Index profile, (b) 19-lobed mode 90 % purity intensity profile for a 10 kW, single frequency ribbon fiber amplifier.

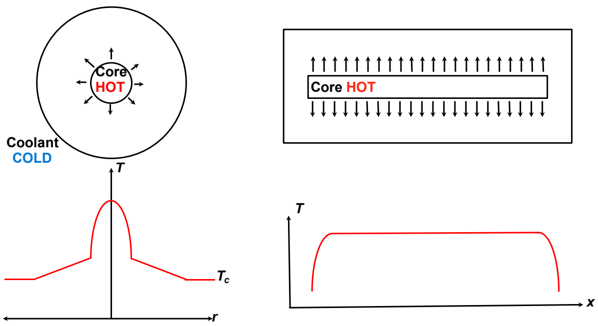

Figure 2: Comparison of circular and ribbon fiber thermal profiles

This design methodology for SBS limited fiber lasers is the same for ribbon core as for circular core geometries. The advantage obtained by utilizing the ribbon core geometry, is increased effective area while maintaining the ability to bend in one dimension. An additional advantage is obtained by increased thermal contact with the guiding region of the fiber. As circular geometry fiber lasers are scaled to higher diameters, the thermal contact with the center of the fiber is reduced. Ribbon fibers however are narrow in one dimension providing excellent thermal contact for nearly arbitrary widths. Figure 2 illustrates this effect. The BPM simulations tracked the temperature through the fiber amplifier, and the peak temperature rise for the 10 kW amplifier was 55^{o} K shown in Figure 3.

Lawrence Livermore National Labs (LLNL) has fabricated several photonic crystal fiber based ribbon fibers with 100 µm wide core regions suitable for approximately 500 W single frequency, single mode, SBS limited lasing. Rectangular core, ribbon fibers are multimode in one dimension, and quasi single mode in the other. The effective index spacing between modes increases with mode number. It is therefore advantageous to illuminate a single high order mode at the input of a ribbon fiber amplifier. Figure 4 shows a cross-sectional image of an example photonic crystal ribbon core fiber fabricated at LLNL.

Ribbon fiber modes take the form of electric fields in the shape of sines and cosines, and can be illuminated by various methods including coupling by pressure induced long period gratings (4), fringes induced by interfering two beams at a small angle, or illumination through a binary phase plate. These methods of illuminating a high order ribbon fiber mode in a novel rectangular core photonic crystal fiber are discussed with modeling and experimental results showing high purity illumination, > 90% , and simulations predict high stability of the ribbon mode during amplification in the presence of modal noise, and non-linear effects. Figure 5 shows the resulting 5 lobed mode with ~90 % purity after a binary phase plate illumination in the fiber shown in Figure 4.

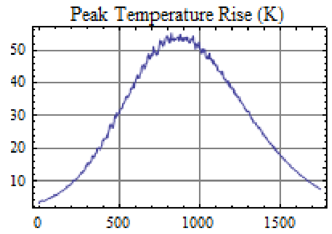

Figure 3: BPM simulation of the temperature rise as a function of longitudinal position in a 10 kW ribbon fiber amplifier

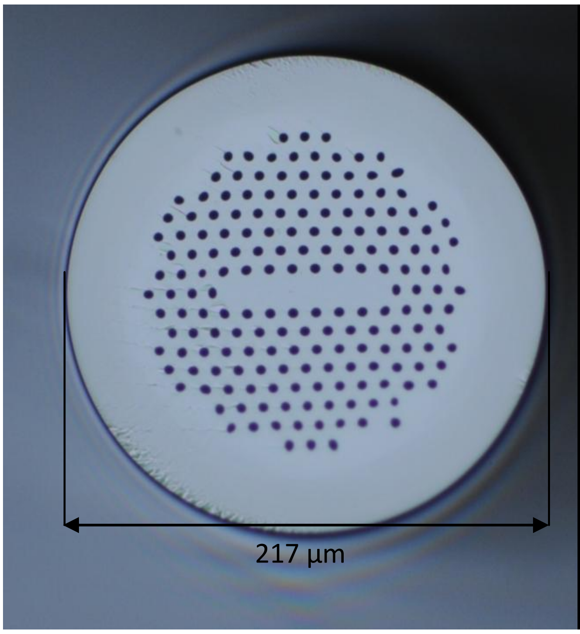

Figure 4: Lawrence Livermore National Lab fabricated ribbon core fiber, ~ 100 µm wide core.

Figure 5: Measured high order mode from fiber in Figure 4, with 90 % modal purity

References:

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(3) Sridharan, A.K., Pax, P.H., Heebner, J.E., Drachenberg, D.R. & Dawson, J.W. Mode-converters for rectangular-core fiber amplifiers to achieve diffraction-limited power scaling. *Proc. of SPIE, Laser Technology for Defense and Security VIII* **8381**, 838103-1-838103-6 (2012)

(4) Bullington, A.L. *et al.* Mode conversion in rectangular-core optical fibers. *Applied optics* **51**, 84-8 (2012)

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